AN INVESTIGATION OF A PLATINUM WIRE RESISTANCE THERMOMETER SYSTEM

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THESIS

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RESISTANCE THERMOMETER SYSTEM

by

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An Investigation of a Platinum Wire

Resistance Thermometer System

by

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ABSTRACT

An analysis of the noise and response characteristics of an atmospheric temperature measuring system manufactured by National Electrolab Associated Limited was conducted.

Noise measurements indicated a marginal signal-to-noise ratio for temperature fluctuations of 0.1C° or smaller. System output voltage varied linearly with sensor resistance changes. Frequencies above 4.5kHz were attenuated with a loss of 3dB occurring at 14kHz.

Whereas the frequency response of the system was more than adequate, a significant improvement in the signal-to-noise ratio can be made by making use of recent electronic improvements. This improvement is considered necessary to obtain more accurate spectra at high frequencies.

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The author also would like to thank Professor Thomas M. Houlihan and Electronics Technician Thomas Christian of the Mechanical Engineering Department for their excellent support. All of the precision electronic equipment used for this thesis was made available by the Mechanical Engineering Department. Such departmental support of thesis work generated by students from other departments is unusual but is an attitude that should be encouraged. The Mechanical Engineering Department is commended for its cooperative spirit and exemplary attitudes.

I. INTRODUCTION

A. BACKGROUND

Knowledge of the air-sea interactions has grown rapidly in the past five years, however, even more knowledge is necessary to parameterize effectively the heat, momentum, and energy exchanges that take place across the air-sea interface.

Studies of the temperature and velocity near the interface have suggested that the important interface parameters lie in a better understanding of velocity and temperature microstructure. Measurement of both quantities at high wave numbers have been complicated by sensor systems with operating parameters which did not permit the precise data recovery necessary for the study of microprocesses.

In 1962, the University of British Columbia began a comprehensive study of air-sea interactions and made measurements of the high wave number spectrum of turbulence at high Reynold's numbers. Pond, et al. (1966) reported measurements taken with a 2.5 micron platinum wire sensor. These supported the predictions of Obukov (1949) and Corrsin (1951) who predicted a - 5/3 power dependence on wave number for temperature spectra corresponding to the inertial subrange. Efforts were continued at the University of British Columbia to extend the temperature fluctuation measurements into the very high wave number region, where viscosity and thermal conductivity are important.

Boston (1970) reported measurements of temperature fluctuations using a platinum wire 0.30 mm in length and 0.25μm in diameter, a diameter 10 times smaller than that considered practical by Hinze (1959). Because the measurements of Pond (1965) had been adversely affected by system noise level before the dissipation region of the temperature spectrum was reached, Boston sought an improved system. Boston worked with and developed several systems but ultimately chose the temperature system developed by National Electrolab Associates Limited of Vancouver, British Columbia primarily because of its low noise level.

Although the signal-to-noise ratio seemed satisfactory for an incremental temperature change of 0.1C°, Boston's criterion, the response of the system was only partially documented. In order to clarify Boston's results, an analysis of this temperature measuring system was carried out.

B. OBJECTIVES

The objectives of this research are twofold:

1. To establish and evaluate the operating parameters of the National Electrolab Associates' Platinum Wire Temperature System Model 116-01.

This work is to establish:

(a) The system frequency response from 0 to 10kHz.

(b) The spectrum noise level from 0 to 10kHz.

(c) The output voltage variation as a function of the platinum wire sensor.

2. To design and develop an improved platinum wire temperature system should the system evaluated prove either marginal or unsatisfactory.

II. PLATINUM WIRE TEMPERATURE SYSTEM

A. GENERAL DESCRIPTION

The platinum wire temperature system (Figure 1) consists of:

1. A multivibrator circuit whose output is an 80kHz square wave for bridge excitation.
2. A balanceable bridge which serves as a modulator.
3. A platinum wire sensor mounted on a Flow Corporation probe which forms one leg of the bridge circuit.
4. A differential amplifier whose gain is fixed at 60dB.
5. A synchronous detector which demodulates the carrier.
6. A lowpass filter which minimizes high frequency components in the output.
7. An operational amplifier with fixed incremental voltage gain of 3, 5, 10, and 20.

These components with the exception of the sensor, probe, and its associated cabling are encased in a metal chassis box (Figure 2).

1. Multivibrator

Two 2N4124 transistors and their associated components (Figure 3) form a sinusoidal 80kHz multivibrator. The sinusoidal output drives a switching transistor 2N4126 which shapes a square wave of constant amplitude.

2. Bridge Circuit

The bridge circuit (Figure 4) is a modified Wheatstone bridge consisting of two 2.21kΩ resistors, the sensor

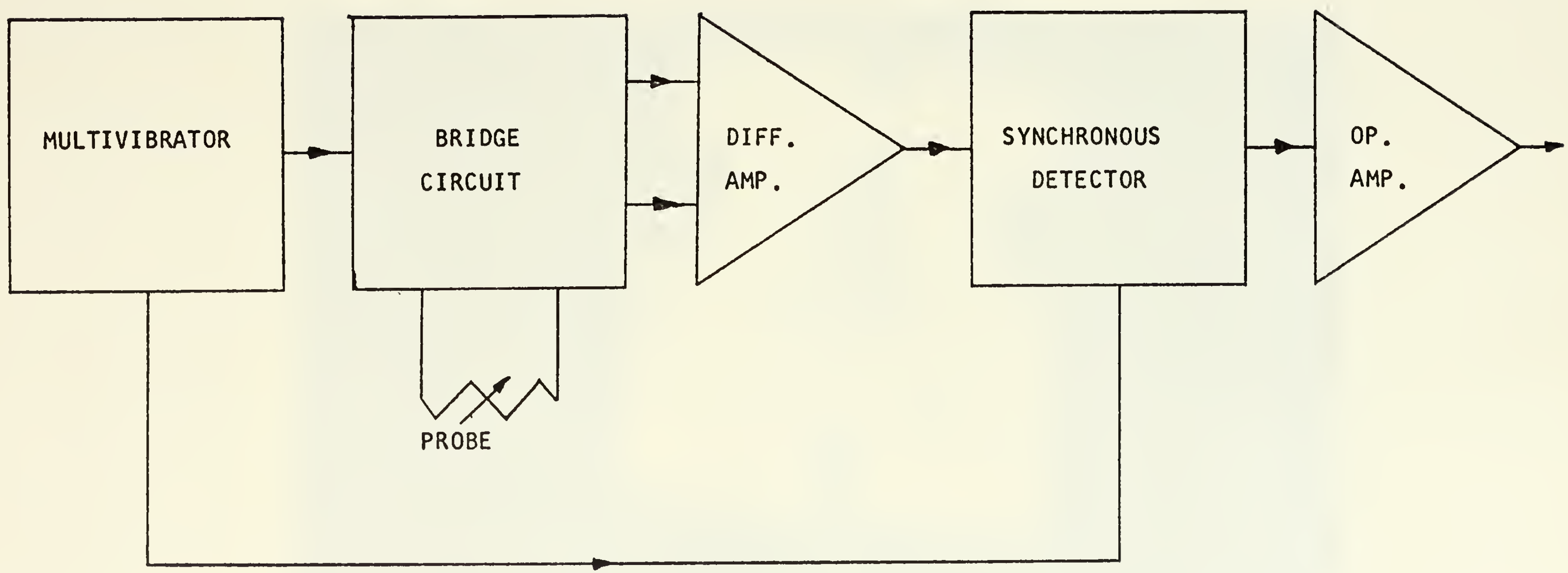


Figure 1. Block Diagram of Platinum Wire Temperature System.

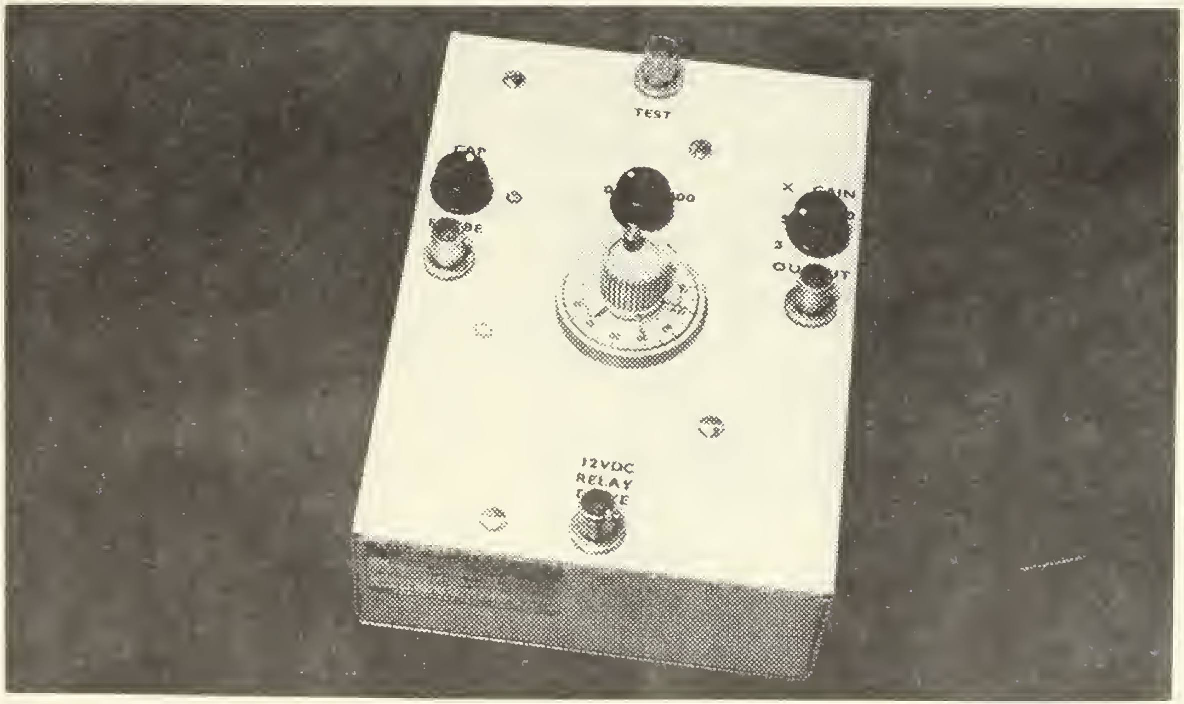


Figure 2. Metal Chassis Containing Temperature System.

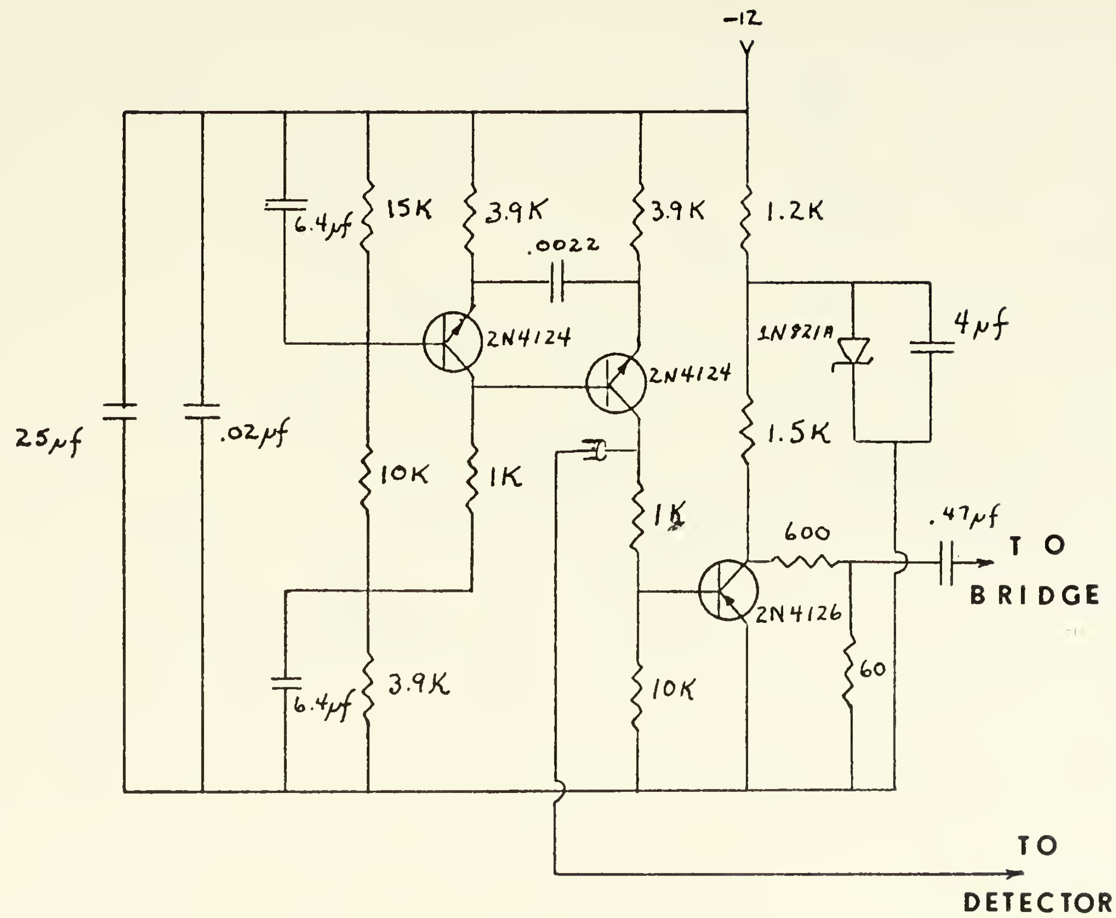


Figure 3. Multivibrator Circuit.

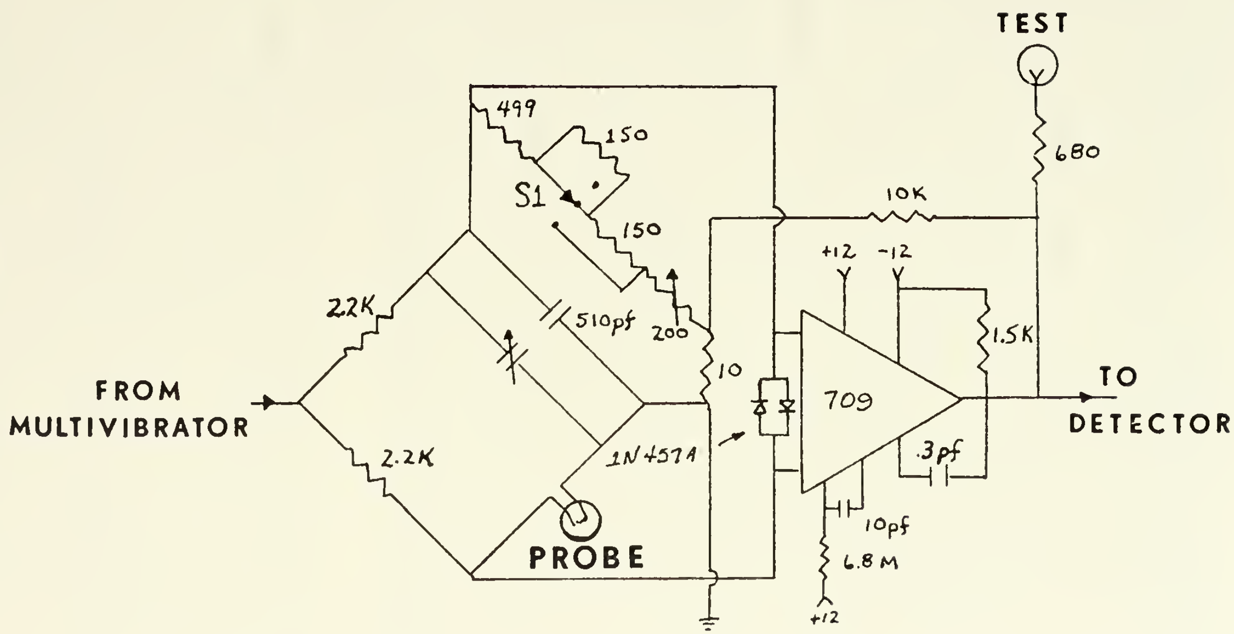


Figure 4. Bridge Circuit and Bridge Differential Amplifier.

resistance, the probe and cable capacitance, and balance adjustment resistors and capacitors. The balance resistance may be varied from 500Ω to 1000Ω by the series combination of a 200Ω variable resistor and one or more selectable fixed resistors. The fixed and variable capacitors paralleling the balance resistance may be used to match the probe and cable capacitance.

3. Platinum Sensor, Probe, and Cabling

The sensor was made from Wollaston wire which consists of a silver jacket about a platinum core. The outside diameter of the jacket was about 45μm. The wire was formed into a pre-stressed V-shape and soldered onto the tips of a Flow Corporation probe. Great care was necessary to insure that no stress was imparted to the wire. The silver jacket was then removed electrochemically from a short length of the wire by placing the wire tip in a bubble of dilute nitric acid and applying a small potential between the wire and the acid solution. Sensor resistances in the range of 600Ω to 900Ω were desired. Only the removal of 0.3 mm to 0.45 mm of the silver jacket was necessary since the resistance of the platinum core was about 600kΩ per foot.

Boston (1970), based on previous experience, anticipated that the maximum frequency of temperature fluctuation likely to be encountered in the atmospheric boundary layer was 2kHz. Boston also calculated the time constant of the 0.25μm wire based on empirical relations to be about 10μsec, a time constant sufficiently short to measure 2kHz temperature signals.

The triaxial cable connecting the probe to the bridge circuit served as a transmission line, however, the cable has a capacitance of 28.5pf per foot and, therefore, required compensation by the fixed and variable capacitors which paralleled the balance resistance.

4. Differential Amplifier

The differential amplifier (Figure 4), is an integrated amplifier with a fixed gain of 60dB. The circuit gain is set by the 10kΩ and 10Ω resistors in the feedback loop. The frequency compensation network composed of the 10pf and 3pf capacitors stabilize the integrated circuit for any amount of feedback.

The differential amplifier circuit was designed by Fairchild, semiconductor especially for the 709 integrated circuit in order to provide a relatively high gain small signal amplifier with a constant gain and excellent closed-loop frequency response.

5. Synchronous Detector

The synchronous detector (Figure 5), recovers the amplified sensor signal. The basic components of the synchronous detector are:

(a) The coupling capacitor which passes the modulated square wave amplified by the bridge differential amplifier.

(b) The 80kHz bandpass circuit formed by a 5mh choke and a 700pf capacitor which attenuated frequencies other than those near 80kHz.

(c) The 2N4222 field-effect transistor which operates as a switch synchronized with the 80kHz oscillator.

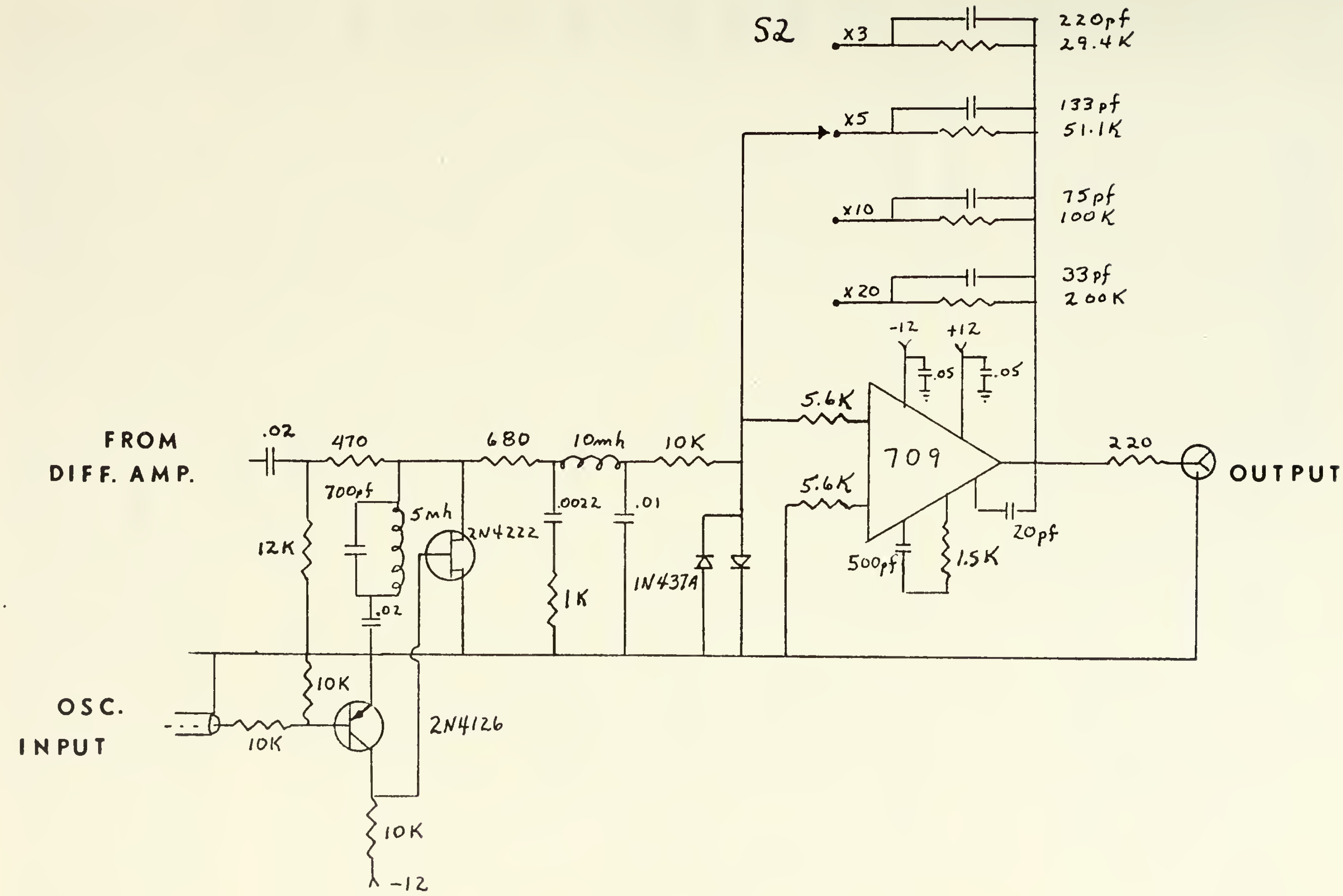


Figure 5. Synchronous Detector and Operational Amplifier.

(d) The lowpass filter which rejects the 80kHz square wave and passes the signal frequency to the output amplifier.

6. Operational Amplifier

The operational amplifier (Figure 5), is a DC amplifier with feedback. The feedback can be changed incrementally to allow voltage gains of 3, 5, 10, and 20. The amplifier includes a frequency compensation network and has closed-loop response which is flat beyond 100kHz.

B. SYSTEM OPERATION

Any temperature fluctuation sensed by a platinum wire sensor causes a resistance change of the wire directly proportional to the magnitude of the temperature change. The resistance change is approximately 2.5Ω per 1C° for a 0.25μm platinum wire of length 0.30 mm. Any resistance change in one leg of a balanced bridge causes the bridge to become unbalanced and a portion of the excitation voltage to be applied to the input of the differential amplifier. Since the input impedance of the differential amplifier is high, the applied signal is directly proportional in magnitude to the magnitude of the unbalancing resistance and its polarity is determined by whether the resistance causing the unbalance is greater or less than the sensor's resistance at balance.

The input to the differential amplifier, a modulated 80kHz square wave, is amplified and coupled to the synchronous detector for demodulation. Since the time constant of the coupling components is much greater than the period of the

80kHz signal, the period of the signal is unaltered, the average level of the output becomes zero regardless of the input level, and the wave top acquires a small linear tilt.

The bandpass circuit, resonant at 80kHz, presents a high impedance path to ground for frequencies near 80kHz and a lower impedance path to ground for other frequencies which are unwanted. The circuit's Q, the ratio of resonant frequency (80kHz) to bandwidth (20kHz by manufacturer's specifications), is low indicating that the impedance, a maximum at 80kHz, does not change rapidly with frequency. At frequencies in the vicinity of 15.9kHz the 700pf capacitor's impedance becomes quite large and the series resonant circuit formed by the 5mh choke and the .02μf capacitor becomes important, approximating a short to ground. As a result of this filtering, the 80kHz modulated signal should arrive at the field effect transistor relatively free of extraneous noise except in the band from 70kHz to 90kHz.

The 2N4222 field effect transistor ultimately switched by the multivibrator via the 2N4126 transistor functions as a phase-sensitive, half wave rectifier by presenting a very high impedance path to ground when not conducting and a very low path when conducting, therefore, alternate half cycles of the 80kHz signal are passed to the lowpass filter or shorted to ground. This circuit which is synchronized with the multivibrator also senses the polarity of the selected half cycles.

The lowpass filter, unable to follow the rapid changes of the rectified 80kHz signal, recreates the wave shape which

originally modulated the carrier and applies the wave form to the input of the operational amplifier for pre-selected amplification.

The output impedance of the operational amplifier (about 300Ω) permits the amplifier to be connected directly to most recording and display devices.

III. TEST EQUIPMENT

In order to establish the parameters of the National Electrolab Associates' temperature system, several test instruments were needed. The precision of much of the selected equipment greatly exceeds that required to test this temperature system. A list of the equipment and pertinent specifications for each follow.

A. OSCILLOSCOPES

1. General Purpose Oscilloscope

The Tektronics Type 531A Oscilloscope (Figure 6), a general purpose instrument for application in the frequency band from 0Hz to 240kHz, was used for all qualitative measurements. Other pertinent specifications are:

a. Rise time of 0.023μsec.

b. Sweep Rate of 0.1μsec to 5 seconds per centimeter.

c. Input impedance approximately 47pf paralleled by a 1MΩ resistor.

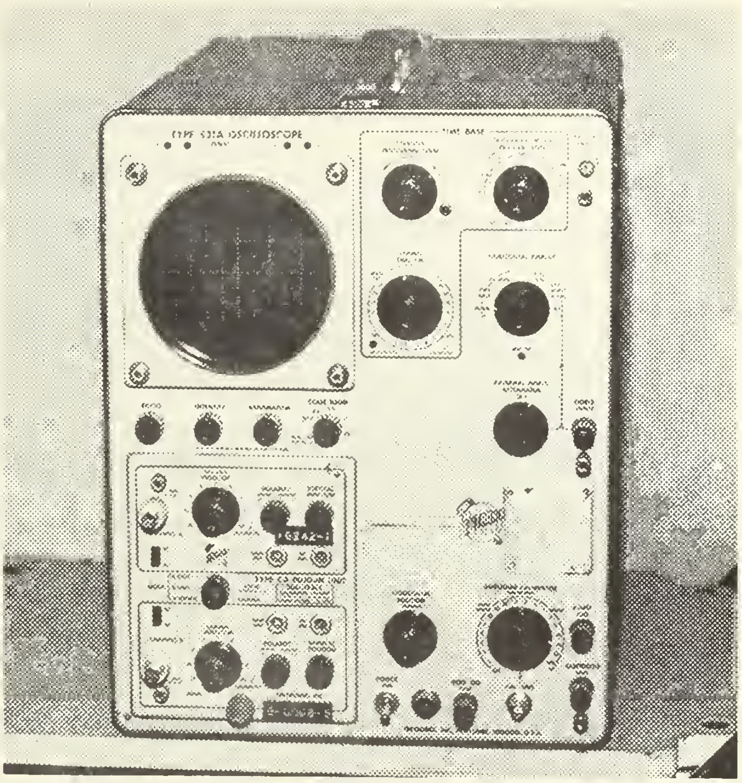
2. Precision Oscilloscope

The Dumont Oscilloscope Type 708A, a 10μV/cm dual beam scope, was used for measurements of voltages and time constants when accuracy was desired. The scope's unique electrometer type input stage gives exceptional amplifier position stability. The Type 708A has selectable bandpass for maximum capability at the high sensitivity. Additional features are:

Figure 6.

Tektronics Model 531A

Oscilloscope



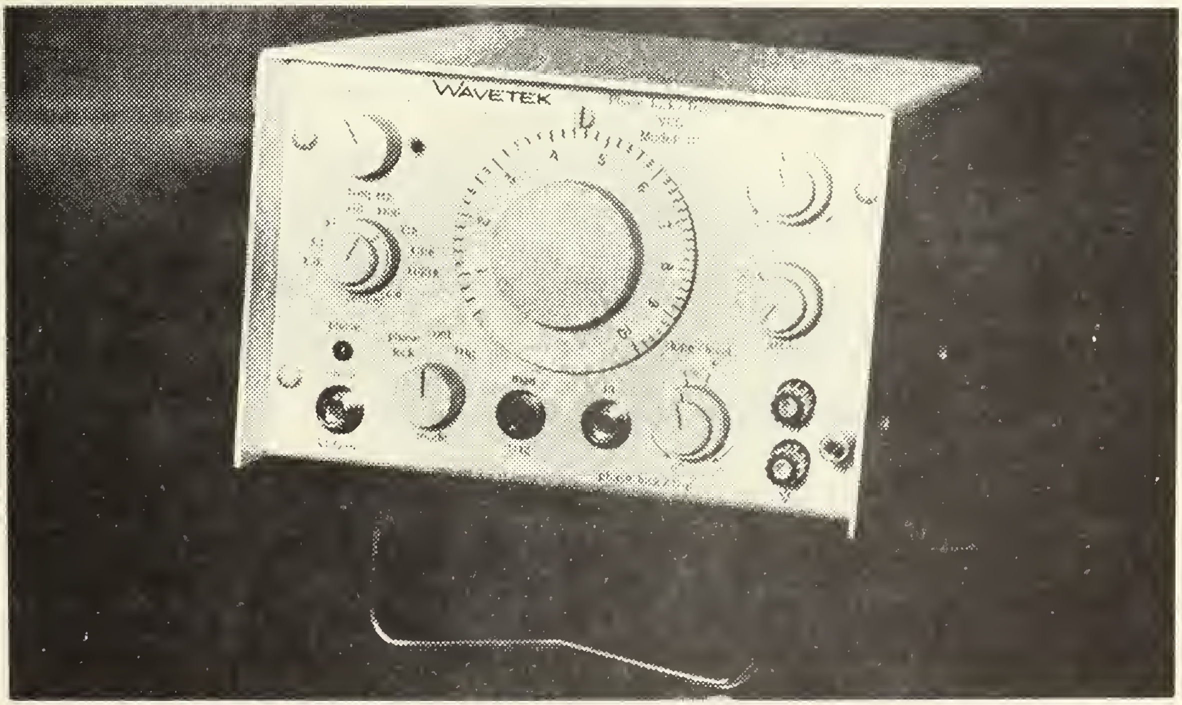


Figure 7. Wavetek Function Generator Model 115.

a. Dual gun CRT.

b. DC or AM stabilized amplifiers.

c. Risetime of 0.7μsec.

d. Input impedance of 1MΩ, constant within ± 3% at all attenuator settings.

B. SIGNAL GENERATOR

The WAVETEK FUNCTION GENERATOR Model 115 (Figure 7), a completely transistorized portable source of semi-precision and stable waveforms in the frequency range from 0.0015Hz to 1 MHz was used extensively during this research. Although 5 waveforms are available throughout the instruments frequency range, only the square, sinusoidal, and sync waveforms in the frequency range from 5Hz to 10kHz were needed.

Various specifications as provided by the manufacturer for this generator are:

Dial Accuracy

± 1% of full scale 0.0015Hz to 100kHz

Peak-to-Peak Voltage Accuracy

± 1% for 2.5 volt and 5 volt outputs

± 1% for 30 volt output into 600ohms at maximum gain

± 10% for 0.5 volt output

Short term Amplitude Stability

± .05% of maximum peak-to-peak values for 10 minutes.

Purity

Sine wave distortion is less than .05%.

Rise time for square waves is less than 10 nanoseconds.

C. VOLTMETERS

1. Root Mean Square Voltmeter

The THERMO-SYSTEMS INC. RMS VOLTMETER Model 1060 (Figure 8), a true rms voltmeter applicable to measurements in the frequency range 0.1Hz to 500kHz, was used for all ac voltage measurements. The averaging time of the voltmeter and also the lowpass cutoff of the voltmeter were determined by proper time constant selection. Long time constants were required when the low frequency response of the meter was needed. To insure that the minimum frequencies of interest were read by the voltmeter, the time constant was selected from the following table provided by the manufacturer:

Time Constant (Seconds)	Low Frequency Cutoff (Hertz)
100	0.1
30	0.3
10	1.0
3	3.0
1	10.0
.3	30.0
.1	100.0

A three time constant waiting period was necessary to insure that the meter reading would be within 2 percent of the final value.

2. Digital Voltmeter

The SIMPSON 2700 DIGITAL SYSTEM (Figure 9), an integrated circuit 4-digit precision instrument for dc voltages

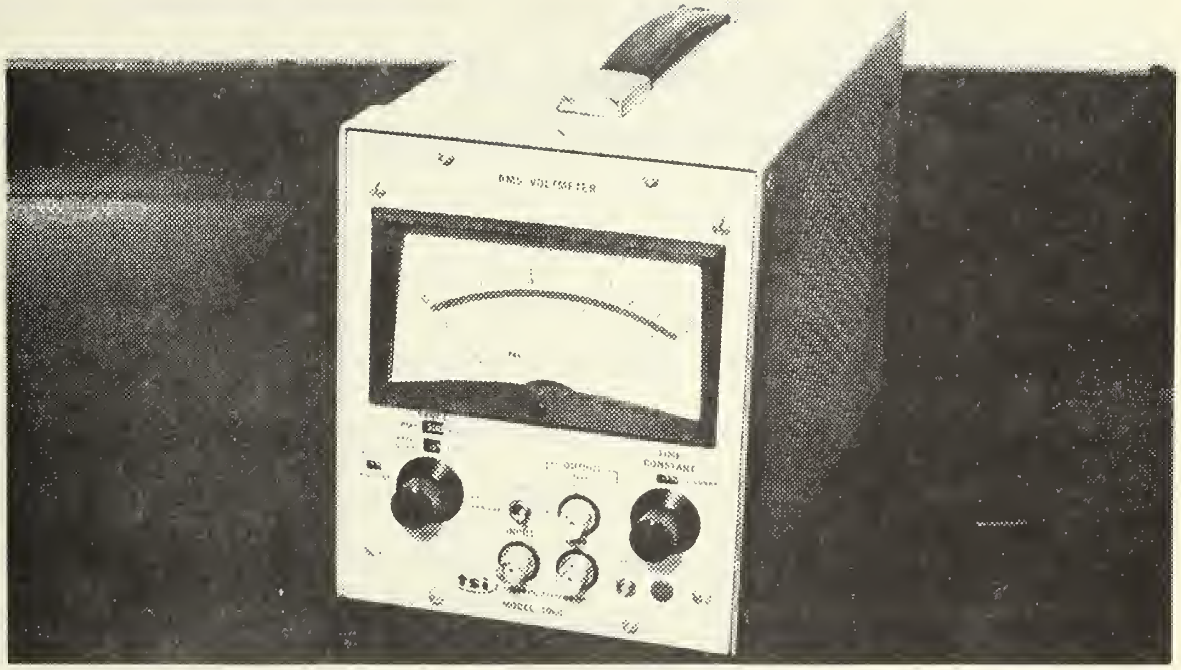


Figure 8. Thermo-Systems Inc. RMS Voltmeter Model 1060

Figure 9. Simpson 2700 Digital System

from 100 microvolts to 1000 volts, was used for all dc measurements. The manufacturer's specifications for the accuracy of this instrument is $\pm$ 0.05% of reading $\pm$ 1 digit at room temperatures.

D. VARIABLE FILTER

The KROHN-HITE CORPORATION FILTER Model 3750(R) (Figure 10), a solid state variable electronic filter covering the frequency range from 0.02Hz to 20kHz was used. Although the filter was operable in four functional modes, only the bandpass mode was used for this research. For minimum bandwidth the highpass and lowpass cutoff frequencies were set equal producing an insertion loss of 6dB with the - 3dB points at 0.8 and 1.25 times the midband frequency. The GAIN switch permitted the gain selection of 1 (0dB position) or 10 (20dB position). The KROHN-HITE CORPORATION'S specifications for noise and hum generated by FILTER Model 3750(R) for a detector bandwidth of 100kHz is:

1. 300μV rms in the OdB gain position.
2. 500μV rms in the 20dB gain position.

The internally generated noise level was measured from 5Hz to 10kHz. These measurements were made with the highpass and lowpass cutoff frequencies set equal and with the filter input shorted. The measuring device used was the THERMO-SYSTEMS INC. RMS VOLTMETER Model 1060 (Figure 8).

E. RESISTANCE BRIDGE

The ROSEMOUNT COMMUTATING BRIDGE Model 920A (Figure 11), a 10kΩ bridge with rangeability similar to a Wheatstone bridge,

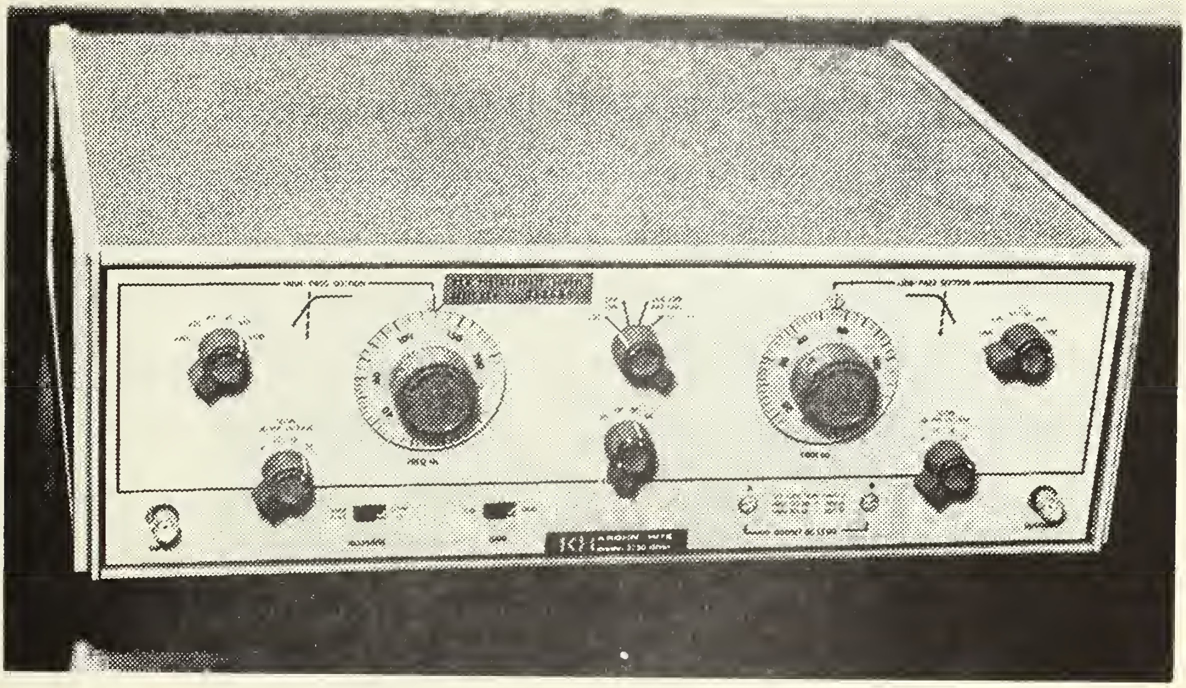


Figure 10. Krohn-Hite Corporation Filter Model 3750(R)

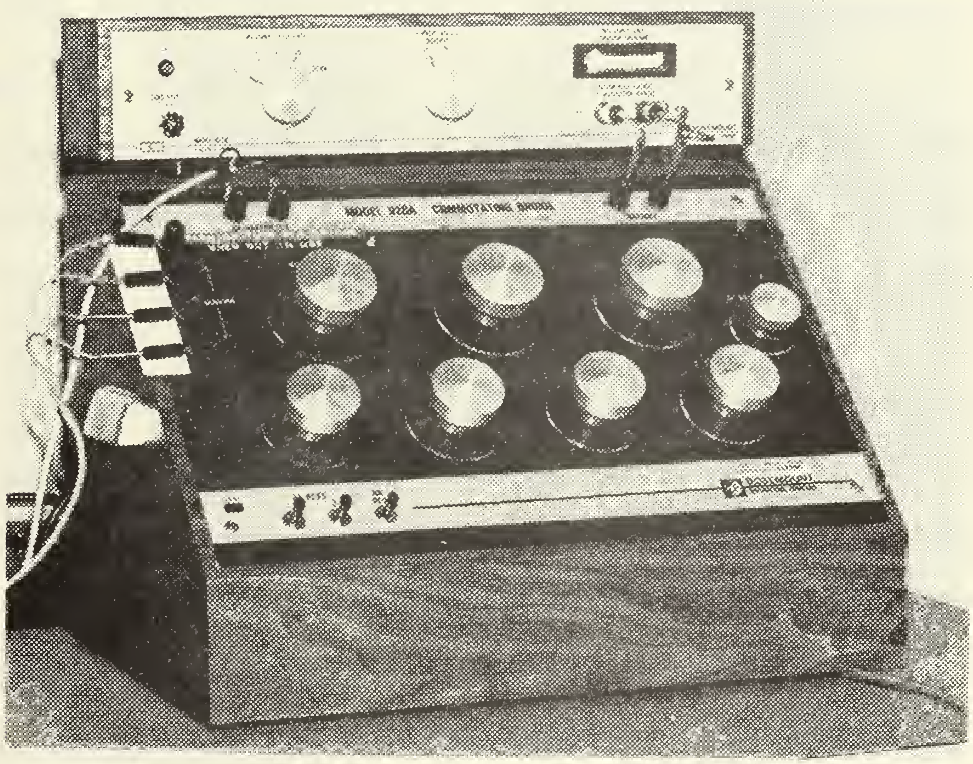


Figure 11. Rosemount Commutating Bridge Model 920A

was used to make various resistance measurements. The instrument gives a direct reading of resistance with a single balance while cancelling all lead resistance. Thermal EMF is eliminated by a simple battery reversal.

The accuracy prescribed by the manufacturer is $\pm$ 0.002% of dial reading or 5 steps on the sixth dial. Calibration in April 1970 by the National Bureau of Standards disclosed the maximum error to be 3 steps on the sixth dial.

F. DUMMY PROBE

The dummy probe (Figure 12) was the device used to replace the Flow Corporation Model HWP probe, its associated cable, and the platinum wire sensor when steady state measurements were taken. The dummy probe was composed of two parts, both mounted on a circuit board.

One part, a length of Evan-Ohm wire (17.5Ω/in.) connected to approximately 60 connectors, permitted small incremental resistance changes (0.5Ω to 2.0Ω) to be made in the range from 500Ω to 1000Ω. Most of the connectors were mounted on the circuit board in a pattern similar to that of a square wave configuration, so that the inductance of the Evan-Ohm wire when soldered to these terminals would be minimized and, therefore, would closely resemble the small reactive parameter of the platinum wire sensor. Since the external size of the connectors did not permit wire lengths shorter than about 0.4 in. (7Ω), a short zig-zag pattern was designed to be placed in parallel with chosen segments of the square wave patterned

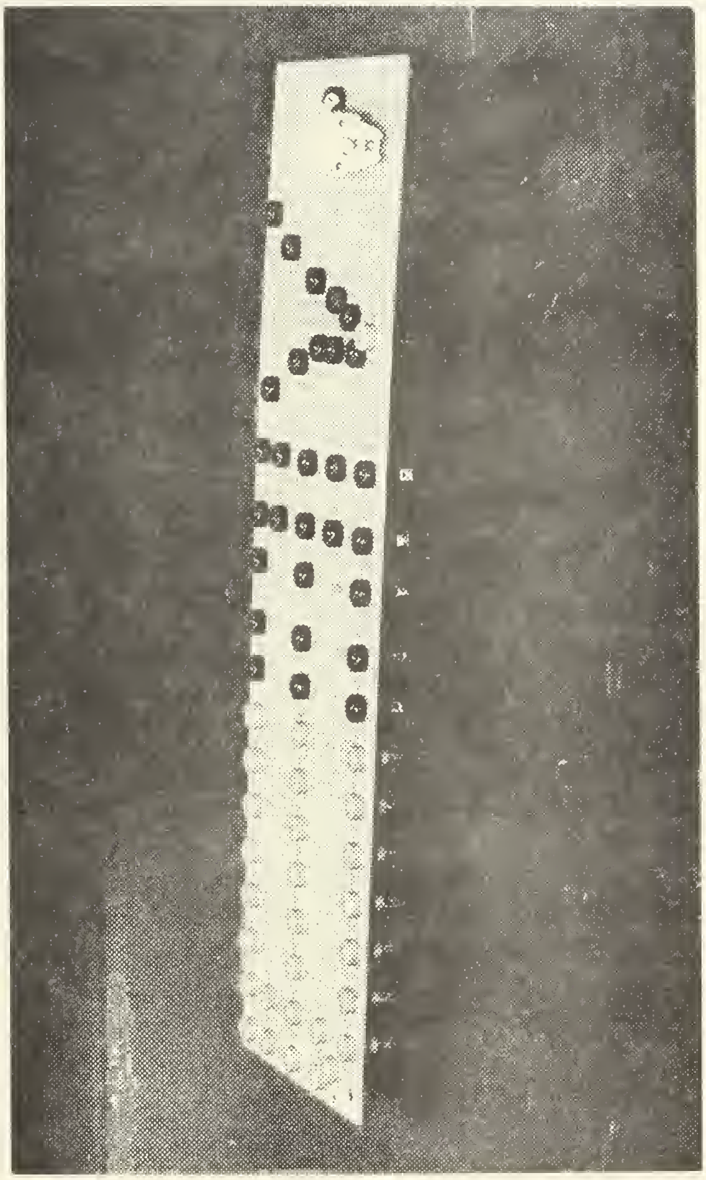


Figure 12. Dummy Probe

wire to permit small incremental resistance changes about any point within the temperature system's range.

The other part of the dummy probe, a collection of two small fixed capacitors and one trimmer all connected in parallel, was used to match the capacity of the dummy probe to that of the Flow Corporation probe and its associated cabling.

IV. TESTING PROCEDURES

The test procedures which follow were used to accomplish part of the first objective of this work. Other simple measurements were made which do not warrant discussion as a test procedure. The results of all tests and measurements will be discussed in Section V.

A. STEADY STATE LINEARITY TEST

Since the temperature of the platinum sensor could not be controlled accurately, the sensor and the probe on which it was mounted were replaced by the dummy probe (Figures 12 and 13) described in Section III. Four sensor resistance values between 500Ω and 1000Ω were chosen arbitrarily as points at which the linearity would be tested. With the dummy probe set to one of the values and attached to the energized temperature system, the bridge circuit was balanced in accordance with the operator's manual. The output voltage was zero when the bridge circuit was properly balanced. The resistance of the dummy probe then was changed by some increment (0.5Ω to 2.0Ω) and the output voltage of the operational amplifier was measured with the Simpson 2700 Digital Voltmeter (Figure 9). After the dummy probe was disconnected from the bridge, its resistance was measured precisely by the Rosemount Commutating Bridge (Figure 11). This procedure was repeated for each resistance change at each of the four chosen balance positions. The data are displayed in Figures 14 through 17.

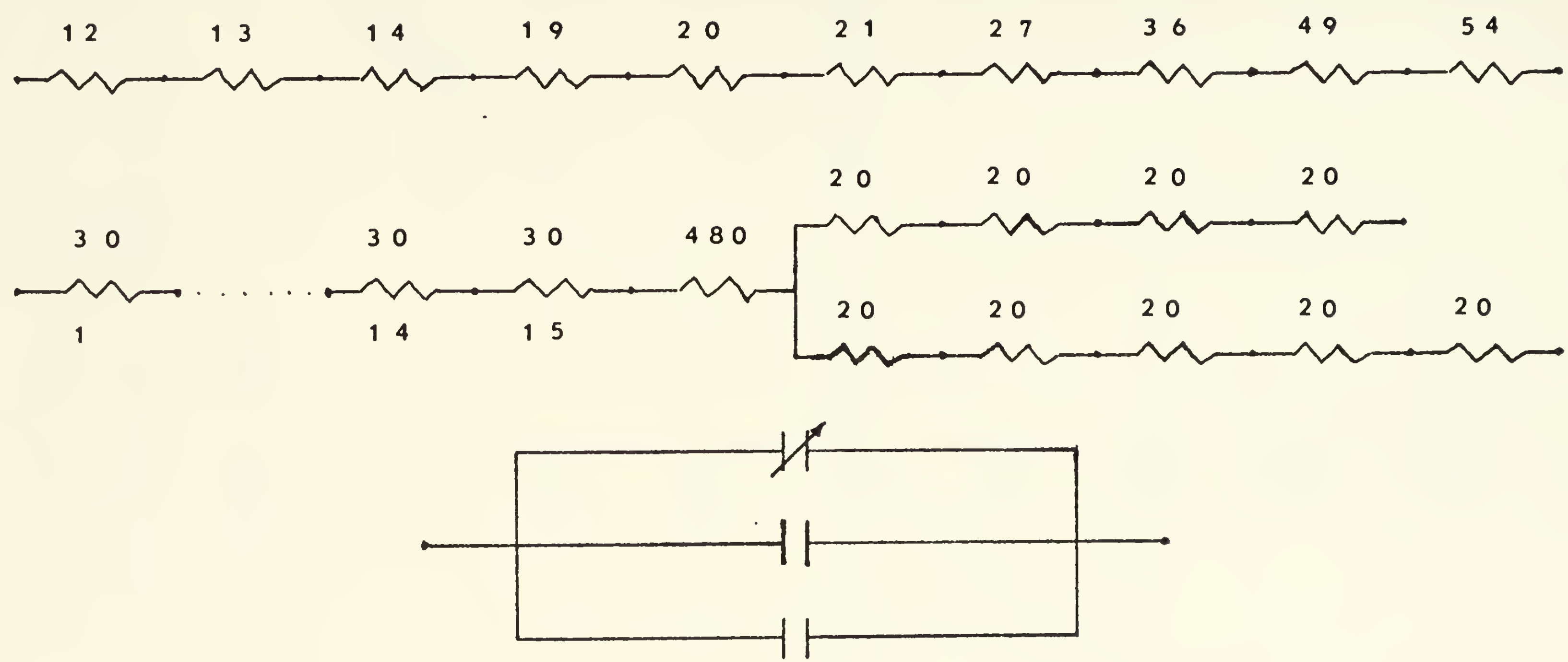


Figure 13. Schematic of Dummy Probe.

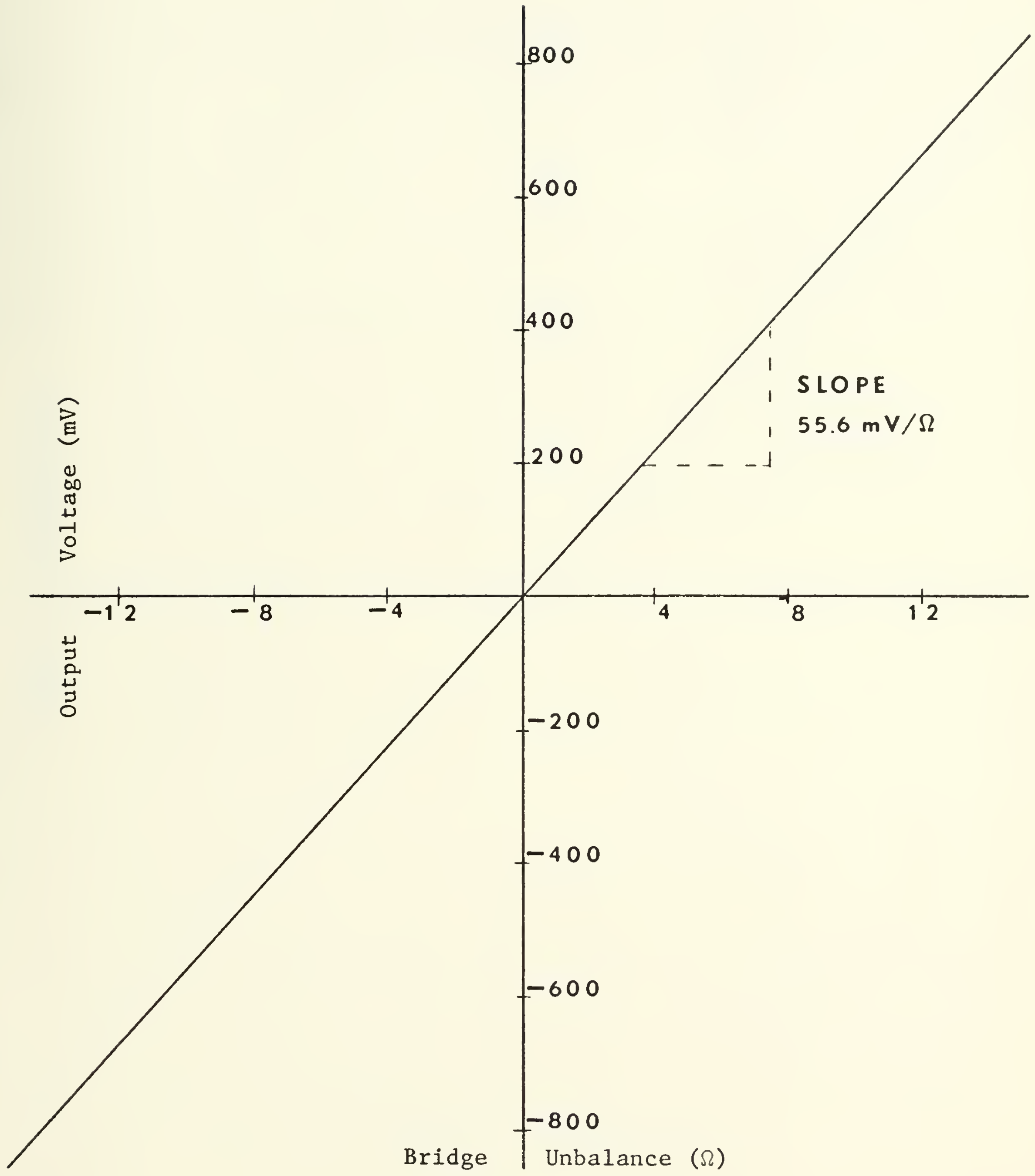


Figure 14. Static System Response for 569.5Ω Sensor

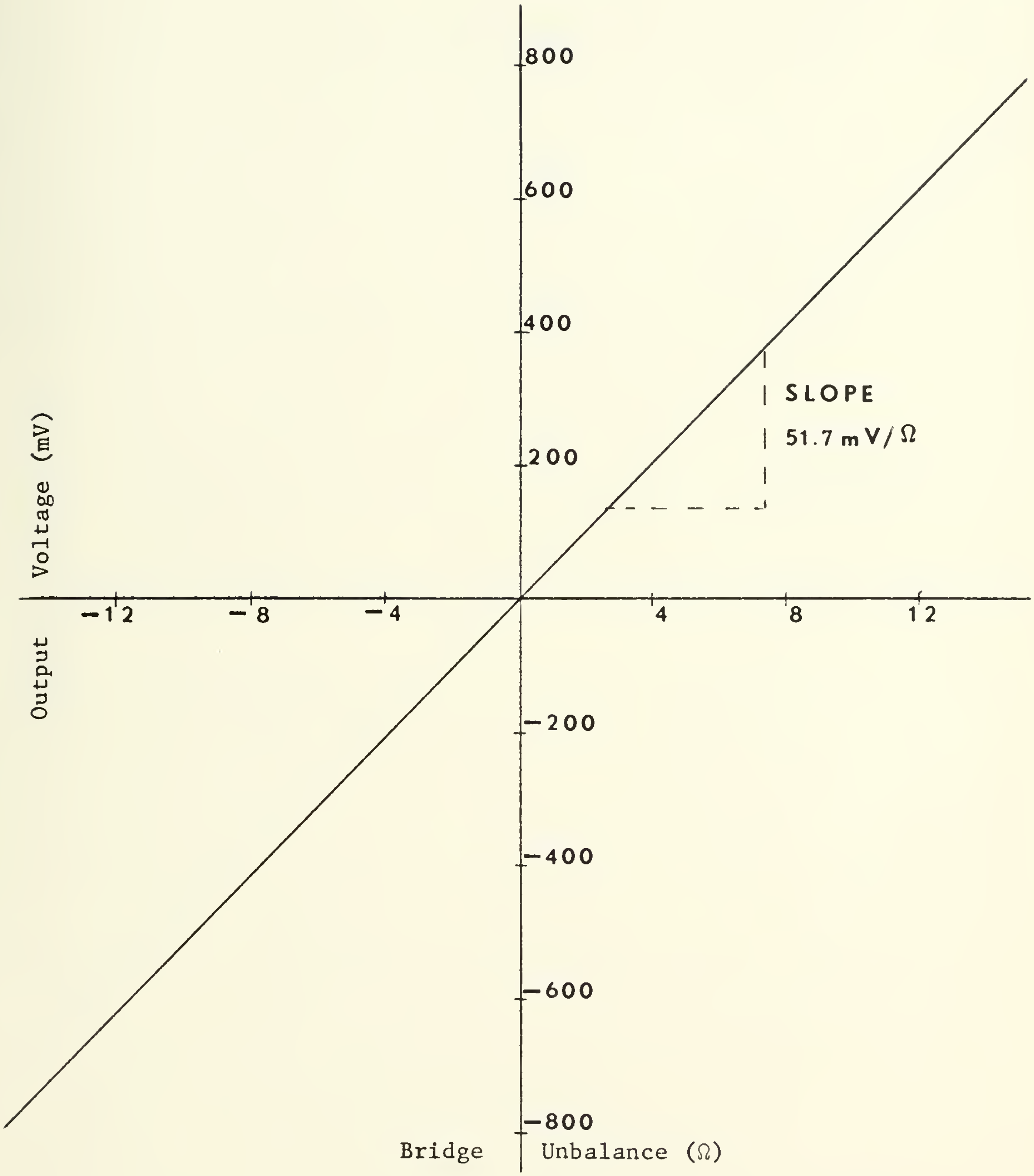


Figure 15. Static System Response for 662.5Ω Sensor

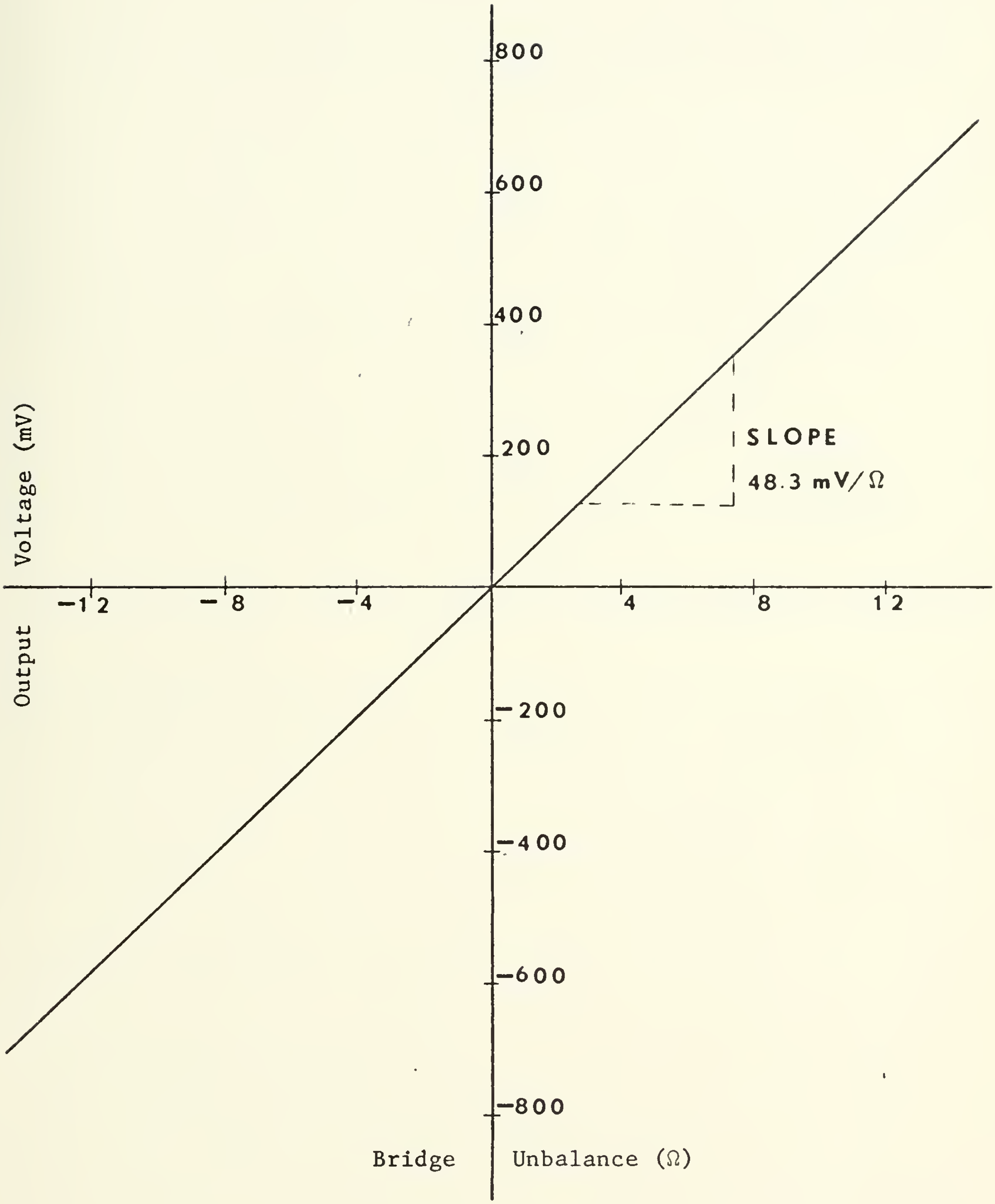


Figure 16. Static System Response for 789.0Ω Sensor

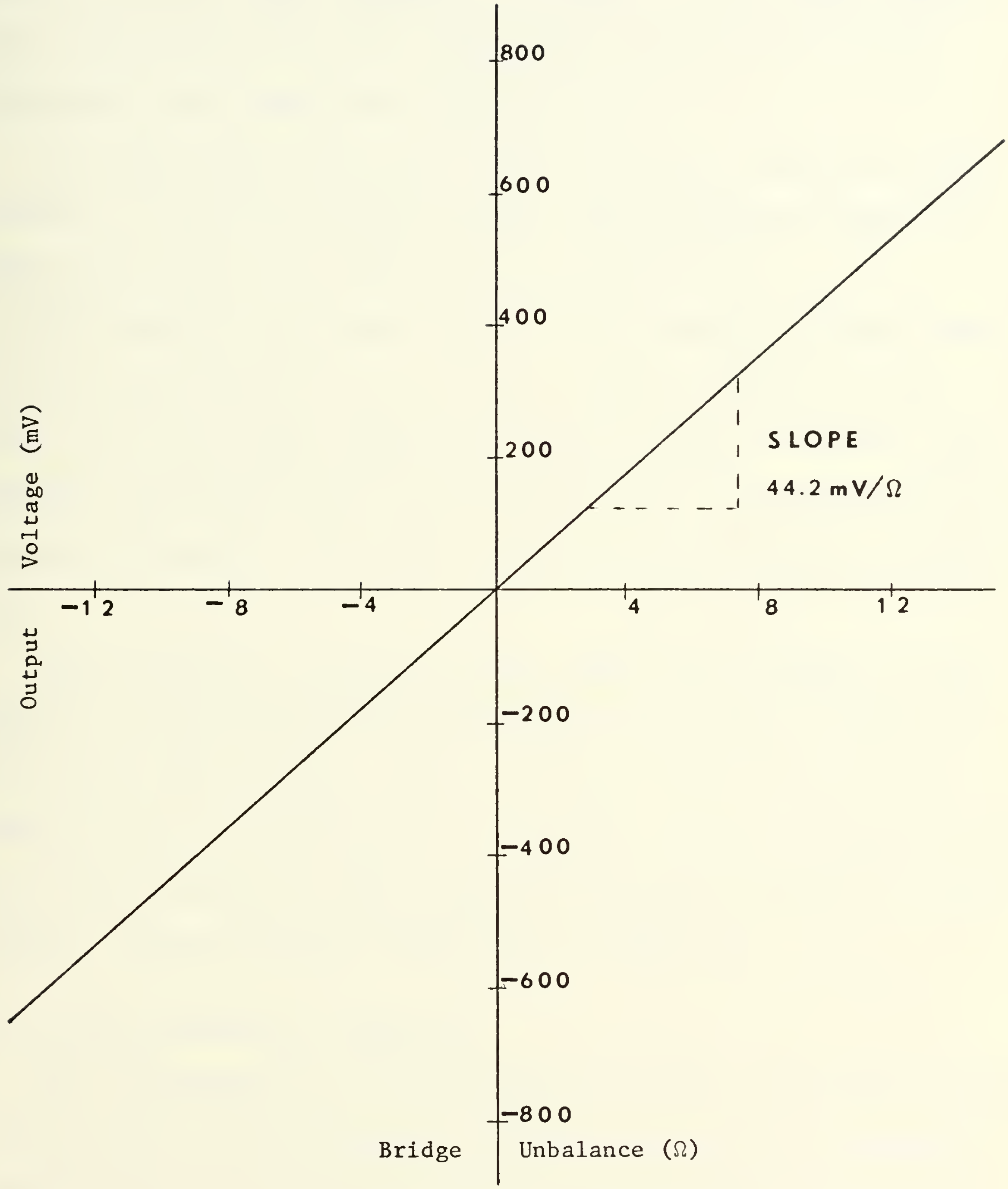


Figure 17. Static System Response for 904.6Ω Sensor

B. SYSTEM NOISE MEASUREMENT

The dummy probe (Figure 12) replaced the platinum wire sensor and its probe assembly to create a steady state condition permitting rms noise measurements free of variations resulting from temperature fluctuations.

The instruments used were the Krohn-Hite Variable Filter (Figure 10) and the Thermo-Systems RMS Voltmeter (Figure 8). Both instruments are described in Section III.

To establish the noise level of the variable filter, the filter input was shorted, and the high- and lowpass filters were set to the same frequency, and the center frequency was changed incrementally after the noise level had been measured at each frequency. The data acquired are displayed in Figure 18.

The Krohn-Hite Variable Filter then was connected to the output of the temperature system after the short across the input had been removed. The procedure used to measure the noise level of the filter was repeated, netting a summation of the noise produced by the temperature system and the variable filter. These data are presented in Figure 19.

C. SYSTEM FREQUENCY RESPONSE

The introduction of a variation into one leg of the bridge circuit which would modulate the 80kHz carrier was deemed the simplest way to determine the system's response. A circuit (Figure 20) replacing the sensor and its probe assembly was developed to modulate the carrier. However, inspection of the bridge output voltage disclosed that the sinusoidal variation

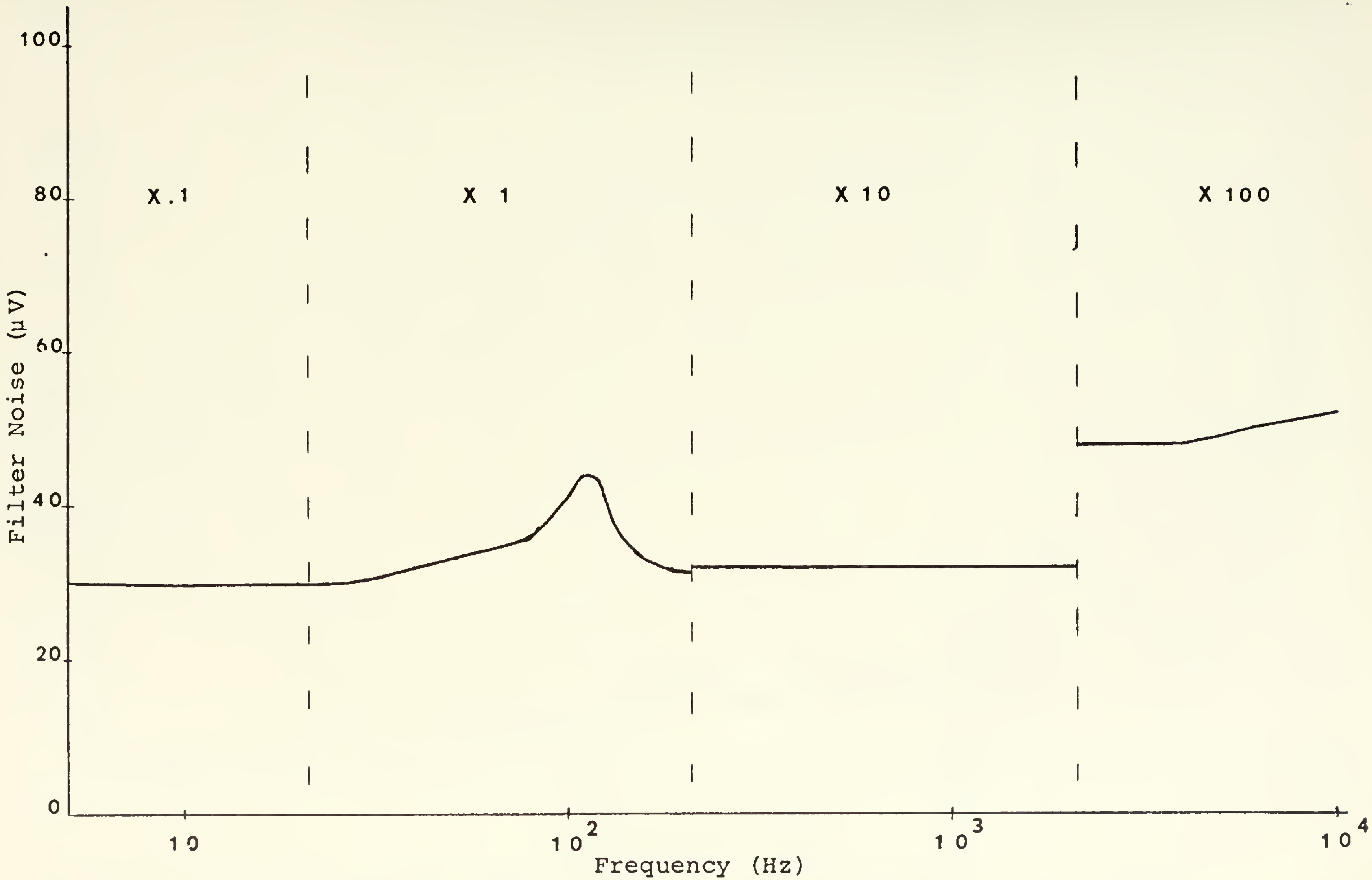


Figure 18. Noise Level of Variable Filter

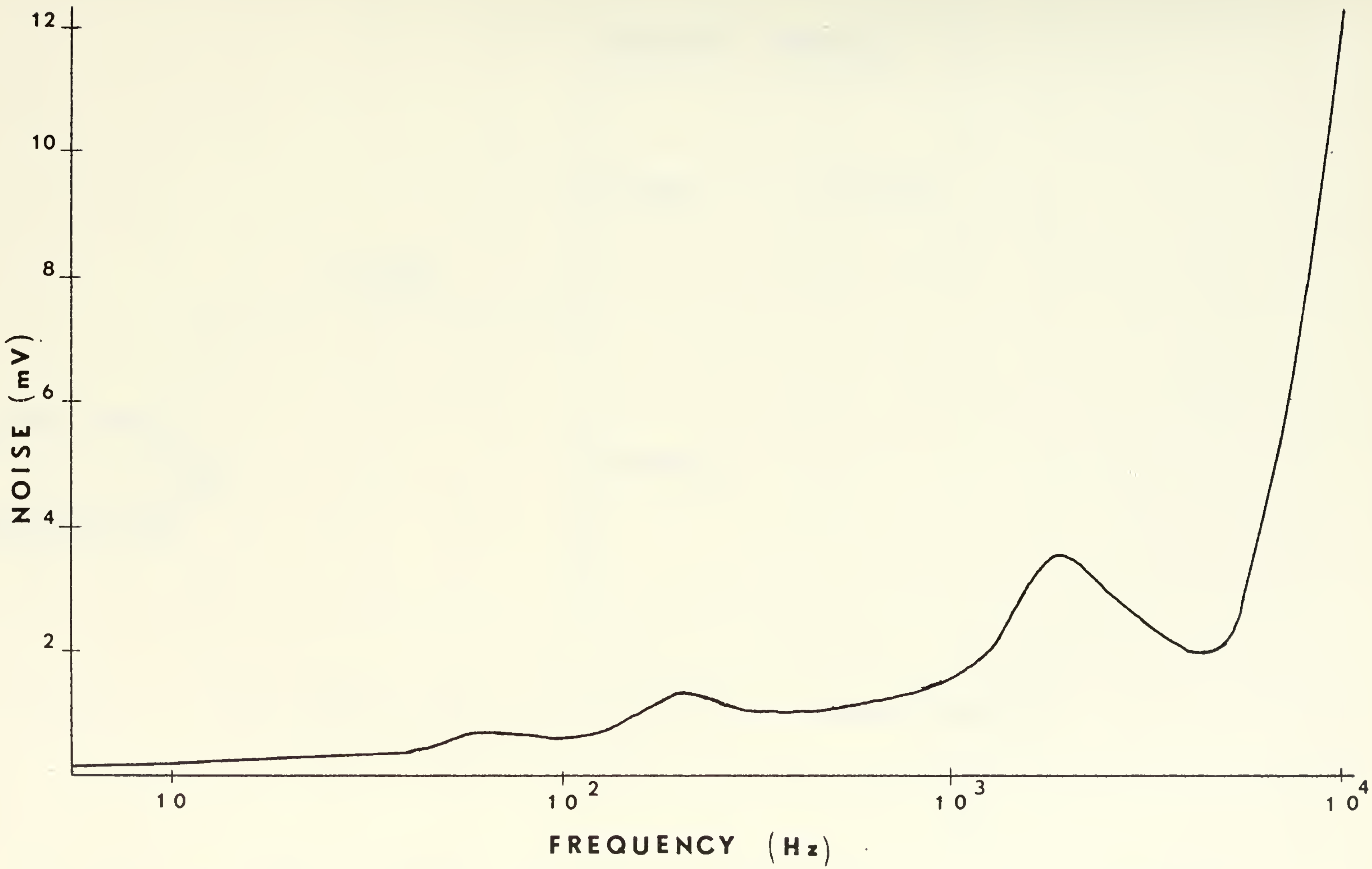


Figure 19. Noise Level of Dummy Probe, Temperature. System, and Variable Filter Combined.

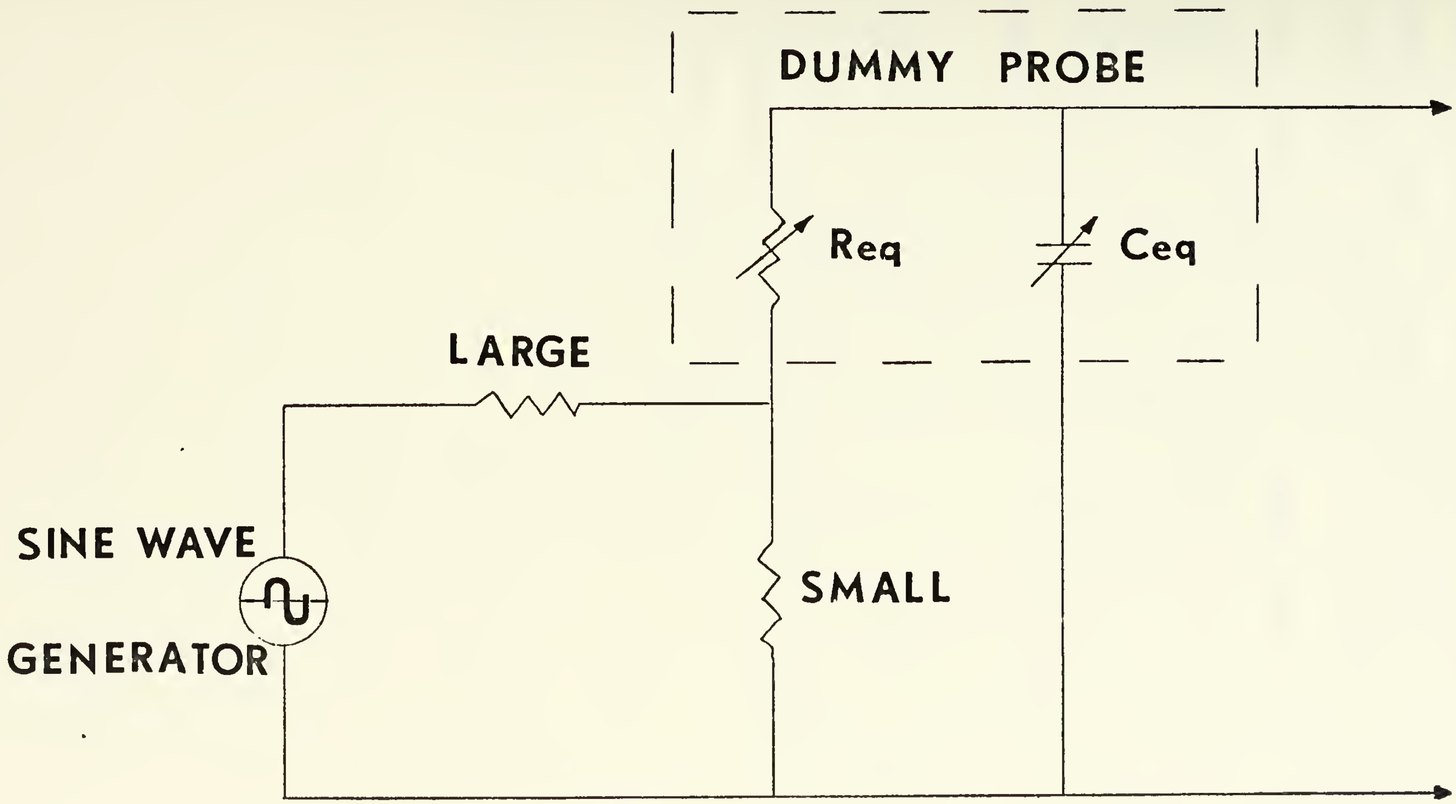


Figure 20. First Circuit Used to Modulate Carrier (Unsuccessful).

was being added to the carrier, rather than modulating it. A second method for modulating the carrier was contrived (Figure 21) using a field effect transistor as a variable resistor whose value could be controlled by a signal generator (Figure 7). This circuit satisfactorily modulated the carrier when a square wave voltage was applied by the signal generator. Inspection of the system's output disclosed that the leading edge of the amplified square wave input signal was rounded by high frequency attenuation. Measurements of the rise time and time constant of this wave in addition to a measurement of the time required for the signal to attain its maximum value were made with the Dumont 708 oscilloscope.

Using the relation, rise time equals 2.2 time constants [Millman and Taub, 1965] and assuming that a period of 3 time constants permitted the signal to reach its maximum value, the system's time constant which governs the frequency response of the system was calculated.

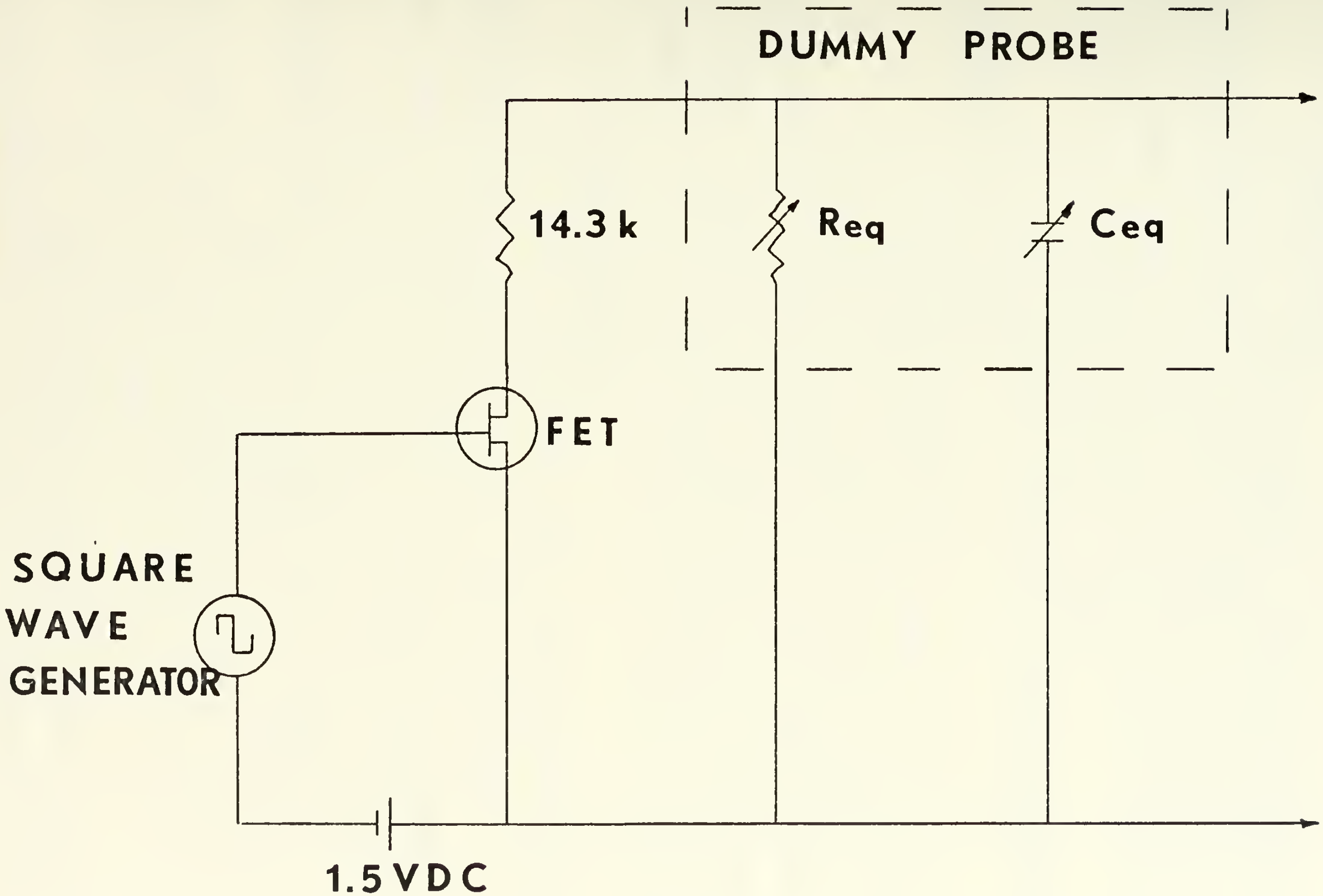


Figure 21. Second Circuit Used to Modulate the Carrier (Successful).

V. TEST RESULTS

A. CIRCUIT ASSOCIATED

1. Multivibrator

The two outputs signals of the multivibrator circuit were inspected with an oscilloscope. Observation of the square wave output which excites the bridge circuit indicated that:

a. No distortion was visible.

b. No frequency change was observed throughout a 30-minute test period.

c. The amplitude of the output was 0.2 mv peak-to-peak.

Observation of the multivibrator output to the detector disclosed that the leading edge of the 80kHz square wave was rounded, suggesting that harmonics of the 80kHz signal were being attenuated. The period of the square wave was unaltered.

2. Bridge Circuit

The most conclusive test involving the bridge circuit was the steady state linearity test described in Section IV and used to acquire the data presented in Figures 14 through 17. These curves verify that the output voltage varies linearly with bridge unbalance and, in addition, suggest that:

a. The input impedance of the differential amplifier is quite high allowing the bridge output voltage to remain linear over a wide range.

b. The differential and operational amplifiers were linear and were not saturated by a sensor resistance change equivalent to a 6 C° temperature change.

c. The 2N4222 field effect transistor is rectifying the 80kHz signal.

Each temperature fluctuation sensed by the platinum wire is directly proportional to the output voltage variation, however, this constant of proportionality varies with the static resistance of the sensor. Figure 22 permits the selection of the proper constant by applying the balance resistance obtained from the switching resistors and potentiometer used to balance the bridge.

The input impedance of the 709 integrated circuit is specified by Fairchild Semiconductor as 350kΩ at 20°C.

3. <u>Differential Amplifier</u>

The differential amplifier output waveform was examined with an oscilloscope when the bridge circuit was unbalanced. The leading edge of the 80kHz square wave was rounded slightly implying that the amplifier's frequency response was not flat at the harmonics of 80kHz. The gain characteristic of the amplifier is displayed as Figure 23, and confirms attenuation above 150kHz.

4. <u>Synchronous Detector</u>

The results of the system frequency response test described in Section III primarily reflect the response of the detector circuit. The modulated carrier observed at the output of the differential amplifier was free of distortion, however, after coupling to the detector, slight low frequency distortion of the modulated carrier was noted.

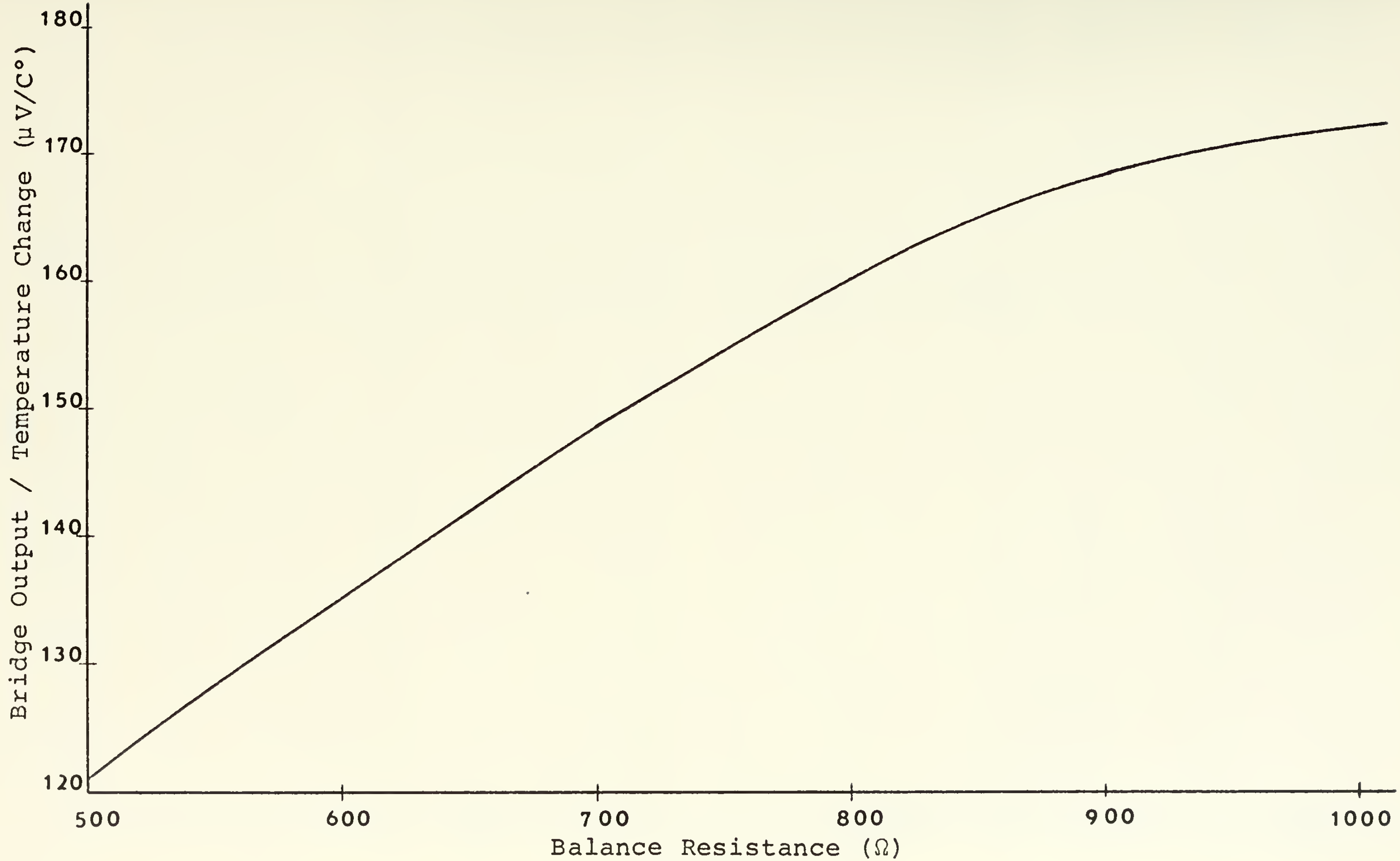


Figure 22. Bridge Constant as a Function of Static Sensor Resistance

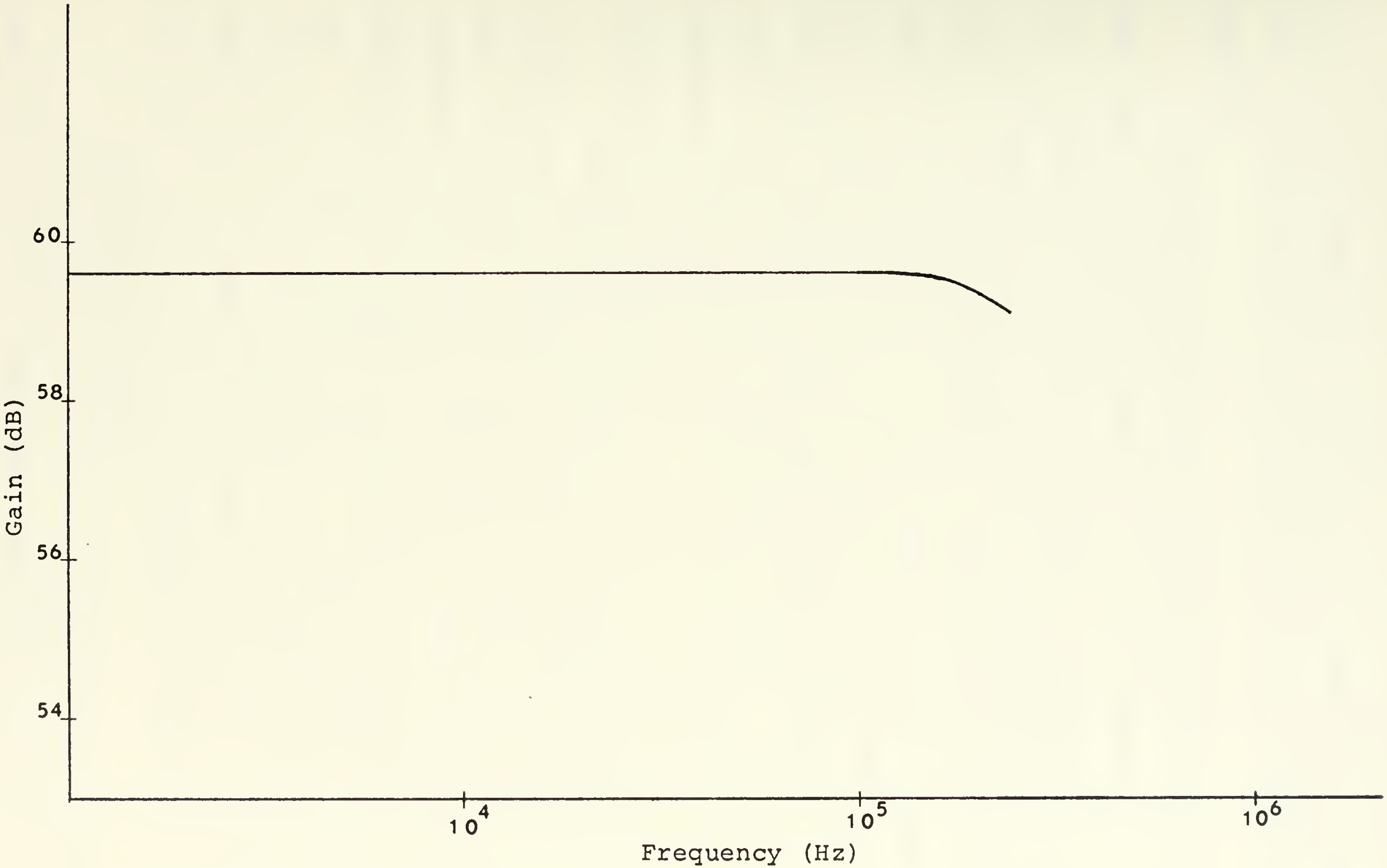


Figure 23. Frequency Response of Differential Amplifier

The synchronous detector rectified the modulated carrier satisfactorily. No significant phase shift between the oscillator input to the detector and the carrier was observed.

The lowpass filter was distorting severely the square wave signal, and 20dB attenuation was noted sporadically. The time constant of the filter was noted to vary from measurement to measurement implying that some component in the filter was changing value intermittently. Inspection of the filter circuit disclosed that a solder connection which apparently had not been disturbed since manufacture was defective. After the solder connection had been repaired, the square wave distortion and attenuation were greatly reduced. The frequency response of the lowpass filter and the operational amplifier are shown as in Figure 24.

Mathematical analysis of the filter based on the value of the circuit components yielded the filter's transfer function. Solving for the frequencies at which the numerator and denominator became zero, netted five break frequencies, a double pole at 15.9kHz, a single pole at 72.3kHz, and a double zero at 37.5kHz [Truxal, 1955]. A Bode diagram of the asymptotes for this break frequencies are shown in Figure 25 and mathematically supported the measured frequency response of the filter and the operational amplifier (Figure 24).

5. Operational Amplifier

The frequency response of the operational amplifier was nearly flat (less than 1dB attenuation) to 10kHz.

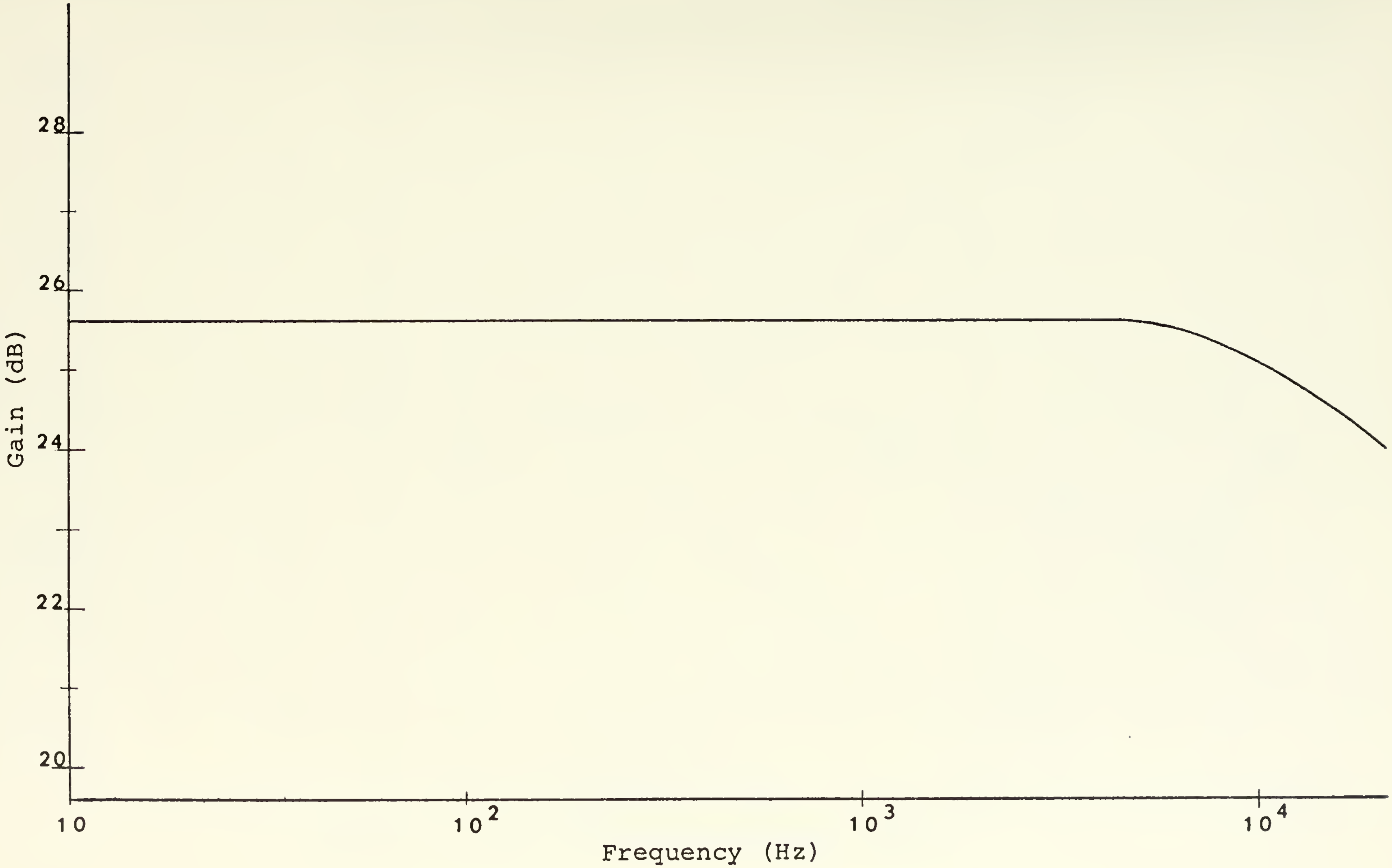


Figure 24. Frequency Response of Lowpass Filter and Operational Amplifier.

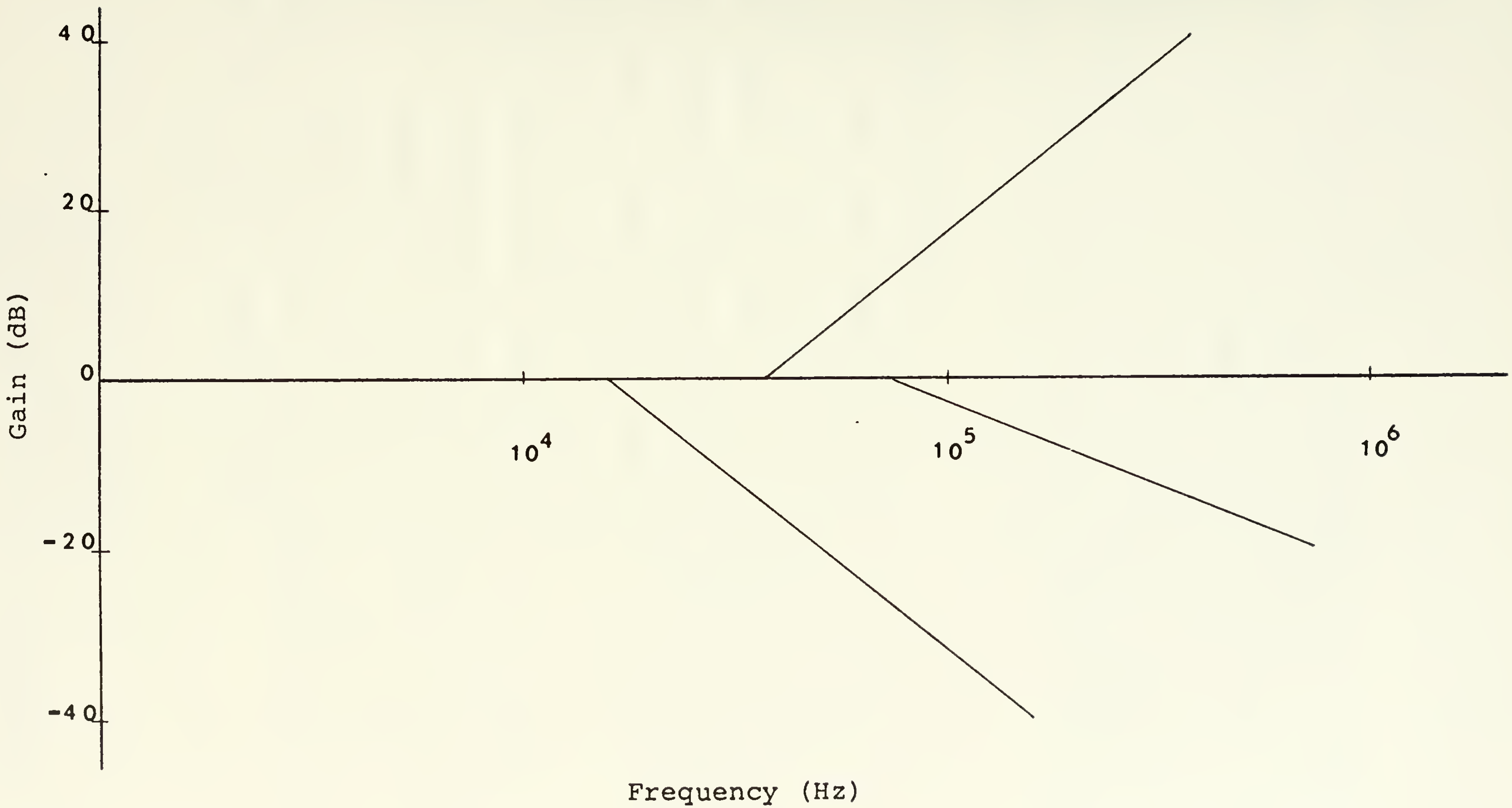


Figure 25. Bode Plot for Lowpass Filter

Mathematical analysis of the amplifier circuit placed the 1dB and 3dB attenuation frequencies at 9.65 kHz and 19.5kHz respectively or higher.

The amplifier's gain measured for each gain selection with the digital voltmeter was found exact to $\pm$ 1mV.

A very low frequency drift of the output voltage was noted. This drift is probably partially attributable to the difficulty in stabilizing a low frequency amplifier.

The amplifier's output was noted to oscillate near 3.1MHz when a gain of 3 was selected.

B. SYSTEM ASSOCIATED

The noise measurement described in Section III was conducted. The data obtained are displayed in Figure 19. The noise level at the input of the differential amplifier results primarily from the resistance noise or Johnson noise of the bridge circuit and the inherent noise of the 709 integrated circuit referred to the input.

The mean-square noise voltage across a resistor is proportional to bandwidth and to the value of the resistor [Terman, 1955]. Assuming the bandwidth is 10kHz and approximating the bridge impedance at 1000Ω, the noise level from the bridge circuit was calculated at room temperature to be 0.40μV rms using the equation [Terman, 1955],

$$e = \sqrt{4kTBR}$$

where k = Boltzmann's Constant

T = absolute temperature

R = equivalent resistance component of impedance across which the noise is produced

B = Bandwidth

Since the peak noise varies randomly, the peak noise will be much larger than 0.40μV rms, however, peaks rarely exceed 4 times the rms value.

The broad band noise added by the 709 integrated circuit referred to the input for a 1000Ω source resistance is approximately 1.0μV rms (Fairchild Semiconductor), a value larger by a factor of 2.5 than that calculated for the bridge generator.

When the two noise sources are combined, the noise power contributions add (rather than the voltage), so that the equivalent input voltage becomes

$$e_{\text{noise equivalent}} = \sqrt{e_n^2 + e_{709}^2} = 1.08\mu\text{V rms} \qquad (1)$$

where $e_n = 0.40\mu\text{V rms}$

and $e_{709} = 1.0\mu\text{V rms}$

Since the overall gain of the circuits which follow the bridge circuit was about 890 whenever the 3X gain position was selected, noise resulting from the bridge circuit and the 709 integrated circuit should generate an output of about 0.96mV rms, a value only slightly different from that measured over the lower part of the frequency range (Figure 19).

As a result of the peak value of a fluctuating signal rarely exceeding 4 times the rms value, a signal-to-noise ratio of 16 was chosen to permit the temperature signal to be distinguishable from the noise at all times. For example, the voltage fluctuation resulting from a temperature variation must equal or be greater than 16 times $e_{\text{noise equivalent}}$ or 17.3μV which corresponds to a 0.128C° temperature change when a 600Ω sensor is assumed. For other values of sensor resistance, refer to Figure 22.

VI. CONCLUSIONS

A. MULTIVIBRATOR

The multivibrator produced a square wave stable in amplitude and frequency to the bridge circuit. The high frequency attenuation of the oscillator output to the detector did not adversely affect the system.

Summary: The multivibrator circuit was satisfactory.

B. BRIDGE CIRCUIT

The bridge circuit provided a simple method of:

1. Modulating the carrier.
2. Changing the sensor resistance variations to voltage fluctuations.

The noise level of the bridge was low (computed to be 0.40μV rms) and, assuming noise-free amplifiers, adequate to measure 0.048C° changes at all times with 600Ω sensor (Figure 22).

Summary: The bridge circuit was satisfactory for the frequency range 0 to 10kHz, but could be improved by changing the values of the bridge resistors.

C. DIFFERENTIAL AMPLIFIER

The 709 integrated circuit did attenuate the harmonics of the 80kHz carrier, but no deleterious effect was noted. The noise level of the integrated circuit was higher by a factor of 3 in noise power than that specified for low noise operational amplifiers now manufactured.

Assuming the output noise level (Figure 19) originates primarily from the 709 integrated circuit, the noise peak observed at 1.8kHz corresponds to 3.82μV rms when referred to the 709 input. Attempting to measure temperature fluctuations of 0.1C°, Boston's criterion, near 1.8hHz becomes impossible without correlation analysis, for the signal-to-noise ratio is about 3.5.

Summary: The differential amplifier is satisfactory for the frequency range 0 to 10kHz, but the noise level is unsatisfactory for temperature fluctuation measurements of 0.1C°, The amplifier could be improved to permit the system to measure temperature changes of 0.05C° using a 600Ω sensor by installing improved integrated circuits, new solid state devices, or a combination of the two (Section VII).

D. SYNCHRONOUS DETECTOR

The low frequency distortion of the modulated signal by the coupling components had no adverse effect on the output.

The lowpass filter passed frequencies slightly higher than predicted mathematically after the defective solder connection was repaired.

Summary: The synchronous detector was satisfactory for measurements in the frequency range from 0 to 10kHz.

E. OPERATIONAL AMPLIFIER

The 3.1MHz oscillation had no adverse effect except it raised the output noise level substantially at frequencies

far above those of interest, nevertheless the oscillation should be stopped with a bypass capacitor.

The drift of a very low frequency which was attributed to the operational amplifier, had no adverse effect on the output since relative temperature fluctuation measurements only were desired.

Summary: The operational amplifier was satisfactory for amplifying the filter output in the range from 0 to 10kHz.

F. GENERAL

The high noise level of the system was a degrading factor for frequencies near and above 1000Hz, when the temperature variations were small.

Data previously taken with the instrument tested should be treated with caution because the frequency response of the system may have varied while the data were taken, thereby distorting the output in an unknown way.

Summary: The temperature system is marginal for the measurements specified by Boston (1970). His measurements should be reexamined in the light of this research.

VII. RECOMMENDATION FOR AN IMPROVED TEMPERATURE SYSTEM

The recommendation which follows is directed toward improving the signal-to-noise ratio of the existing system in order that smaller temperature fluctuations may be measured. The frequency response of the system (flat to 4.5kHz) could easily be improved should the measurement of higher frequencies be desired.

Recent developments in the transistor research field have led to a greatly improved depletion type metal-oxide-semiconductor (MOS) field effect transistor. The MOS FET has exceptionally low noise parameters and excellent thermal stability.

A comparison of the noise figure of a MOS FET suitable for use in this system with that of the 709 integrated circuit suggests that the noise level at 1.0kHz (the frequency near which noise has become dominant) resulting from the installation of a MOS FET with a gain of 30dB would be approximately 0.1μV rms. Therefore, the noise level of the system referred to the bridge output would become 0.41μV rms which corresponds to a temperature change of 0.048C° using a 600Ω probe. This was obtained from equation (1).

$$e_{\text{noise equiv.}} = \sqrt{(0.40\mu V)^2 + (0.10\mu V)^2} = 0.41\mu V \text{ rms}$$

$$\text{and } \frac{S/N \times e_{\text{noise equiv.}}}{e_{\text{signal}}\ (600\Omega)} = \frac{16 \times 0.41\mu V}{135\mu V/C^\circ} = 0.048\ C^\circ$$

This compares with 0.128C° for the original case thus resulting in an increase in the power (spectrum) of almost a factor of five.

The addition of a MOS FET pre-amplifier between the bridge circuit and the differential amplifier would reduce the output noise resulting from the first stage of amplification and is highly recommended.

An alternative improvement would consist of replacing the 709 integrated circuit with an improved integrated circuit, such as a 739. The increase in the signal-to-noise ratio is very nearly the same as for the MOS FET pre-amplifier addition before the 709. The ultimate improvement would be to use the MOS FET in conjunction to an improved integrated circuit. The gain of this over the pre-amplifier addition would be marginal, but probably worthwhile.

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13. ABSTRACT

An analysis of the noise and response characteristics of an atmospheric temperature measuring system manufactured by National Electrolab Associated Limited was conducted.

Noise measurements indicated a marginal signal-to-noise ratio for temperature fluctuations of 0.1C° or smaller. System output voltage varied linearly with sensor resistance changes. Frequencies above 4.5kHz were attenuated with a loss of 3dB occurring at 14kHz.

Whereas the frequency response of the system was more than adequate, a significant improvement in the signal-to-noise ratio can be made by making use of recent electronic improvements. This improvement is considered necessary to obtain more accurate spectra at high frequencies.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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platinum wire thermometer						
temperature system noise						
temperature system frequency response						

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